HIGH-STRENGTH BOLTED CONNECTION STRUCTURE WITH NO FIRE PROTECTION

TECHNICAL FIELD

The present invention relates to a high-strength bolted connection structure with no fire protection that can be applied to the case of a high-strength bolted connection of a column to a beam member or to beam members constituting a steel structure for which fire resistance is required, directly or indirectly, via a join metal such as a T-shaped join metal or a splice-plate. The high-strength bolted connection structure with no fire protection of the present invention includes both a friction type high-strength bolted connection structure with no fire protection and a tension-type high-strength bolted connection structure with no fire protection.

BACKGROUND ART

In a steel structure for which fire resistance is required, when the constituent pillars or beam members are exposed to high temperature at the time of a fire and their strength is lowered, they can no longer function as the steel structure adequately. Thus, conventionally, such steel members have been protected from a high temperature by means of a complicated fire protection provided on the steel members themselves or by provision of protective structure using fire resistant material.

However, provision of such a fire protection on steel members or a protective structure for steel members leads inevitably to an increase in material cost as well as in construction cost. Therefore, recently, several fire-resistant steels having excellent high-temperature strength have been developed which steels have an increased high-temperature strength for a time period corresponding to duration of a fire, and which are mainly directed to realization of a steel structure with no fire

protection. Thus, the same excellent high-temperature strength is also required for a high-strength bolted connection of steel members formed of such fire resistant steels.

As regards high strength bolts and nuts, Japanese Patent Publication No. 02-247355 (claim 1, Table 7 and Fig. 1), for example, has proposed a Mo-added steel, suitable to be used for bolts and nuts, which has a bolt tensile strength of 1000 N/mm^2 or higher at room temperature, and has excellent high-temperature strength at temperature of 600°C or higher. However, this steel does not have adequate high-temperature strength, and requires addition of expensive alloy elements such as Ni, V, etc. in order to obtain increased high-temperature strength, which gives rise to the problem of increased cost.

Japanese patent Publication No. 05-51698 (claim 2 and Table 2) and Japanese patent Publication No. 05-98389 (claim 1 and Table 2) have proposed a steel material, suitable to be used for bolts and nuts, which has a bolt tensile strength of 1000 N/mm^2 or higher at room temperature, and has yield strength of 400 N/mm^2 or higher at temperature of 600°C. However, this steel requires addition of special elements such as Nb, W, etc., and thus gives rise to the problem of increased cost. Also, high temperature strength is still insufficient.

On the other hand, although, in the case of above-described conventional high-strength bolts having known fire resistance, the bolt tensile strength may sometimes become as high as about 1100 N/mm^2, there is another problem, that is, the problem of "delayed fracture", that, even if the bolt is used under stress equal to or lower than the yield stress, after a certain time period has elapsed from clamping, the bolt may suddenly break, which does not permit the bolt to be used as an important joint member of a steel structure. Thus, one is forced

to adopt conventional bolt tensile strength of about 1000 N/mm^2 as the upper bound, so that the number of bolts and length of the joint metal member is inevitably increased. Thus, there is still a strong need for a reduction in cost as well as a reduction in the work execution time.

The high-strength bolts and nuts as disclosed in above-described known literature are all characterized by the amount of added alloy elements, and in addition to the essential problem that, in order to improve fire resistance, the amount of expensive additive elements, and hence the material cost, must increase, there is another problem that the phenomena of delayed fracture may occur.

It is therefore an object of the present invention to provide a high-strength bolted connection structure with no fire protection using an ultra-high-strength bolt which does not require fire protection or a protective structure of refractory material and which can resolve the problem of delayed fracture and can assure adequate strength at a temperature of 650°C while allowing a reduction in material cost as well as reduction in the work execution time.

SUMMARY OF THE INVENTION

In order to attain above object, the present invention provides (1) ~ (9) as described below.

(1) A high-strength bolted connection structure with no fire protection, being a fire resistant high-strength bolted connection structure of a steel structure having columns and/or beams, characterized in that an ultra-high-strength bolt with excellent fire resistance is used, which bolt has bolt tensile strength (TS) of 1200 N/mm^2 or higher at room temperature and which has a bolt shear proof stress (bτt) at 650°C satisfying equation <1> below:

$$b\tau t \geqq \mu \times N_0/(\nu \times bAs) \quad <1>$$

where $b\tau t$: bolt shear proof stress at high temperature (N/mm^2)

$b\tau t = TSt/\sqrt{3}$

TSt : bolt tensile strength at high temperature (N/mm^2)

μ : coefficient of slip at room temperature

N_0 : design bolt tension (N)

ν : safety factor for long term load

bAs : cross-sectional area of bolt shank (mm^2).

(2) A high-strength bolted connection structure with no fire protection according to (1), wherein, in said high-strength bolted connection structure, the allowable long term shear force (Qs) of said beam at room temperature satisfies equation <2> below:

$$Qs \leqq \{ns \times b\tau + (nf - ns) \times b\tau t\} \times bAs \quad \langle 2 \rangle$$

where Qs : allowable long term shear force of the beam at room temperature(N)

$Qs = fs \times Ab$

fs : allowable long term shear proof stress of the beam (N/mm^2)

Ab : cross-sectional area of the beam (mm^2)

ns : number of tension bolts in the floor slab on the upper flange side of the beam

$b\tau$: shear proof stress of the bolt at room temperature (N/mm^2)

$b\tau = TS/\sqrt{3}$

TS : tensile strength of the bolt at room temperature (N/mm^2)

nf : number of tension bolts on the upper flange side of the beam

$b\tau t$: shear proof stress of the bolt at high temperature (N/mm^2)

$b\tau t = TSt/\sqrt{3}$

TSt : tensile strength of the bolt at high temperature (N/mm^2)

bAs : cross-sectional area of bolt shank (mm^2).

(3) A high-strength bolted connection structure with no fire protection according to (1) or (2), wherein said high-strength bolted connection structure is composed of a set of a high-strength bolt, a nut and a washer, and joint metal, and wherein said nut and washer are a general structural hexagon nut and a structural plain washer each having no defined fire resistance.

(4) A high-strength bolted connection structure with no fire protection according to (1) or (2), wherein said high-strength bolted connection structure is composed of a set of high-strength bolt, a nut and a washer, and joint metal, and wherein a part or all of said joint metal is formed of a steel material having an assured high temperature strength.

(5) A high-strength bolted connection structure with no fire protection according to (1) or (2), wherein, in said high-strength bolted connection structure, a part or all of said columns and/or beams used are formed of a steel material having an assured high-temperature strength.

(6) A high-strength bolted connection structure with no fire protection according to (1) or (2), wherein said high-strength bolt contains, in % by weight, C: 0.30 ~ 0.45%, Si: less than 0.10%, Mn: more than 0.40% ~ less than 1.00%, P: less than 0.010%, S: 0.010% or less, Cr: 0.5% or more ~ less than 1.5%, Mo: more than 0.35% ~ less than 1.5%, V: more than 0.3% ~ 1.0% or less, with the balance being Fe and unavoidable impurities, and wherein said high-strength bolt is an ultra-high-strength bolt having excellent fire resistance and a delayed fracture resistance satisfying equations <3> and <4> below:

$TS \leqq (1.1 \times T + 850)$ <3>

$$TS \leqq (550 \times Ceq + 1000) \quad \text{<4>}$$

where TS : tensile strength of the high strength bolt at room temperature (N/mm^2)

T : tempering temperature (°C)

Ceq : carbon equivalent (%)

$$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14).$$

(7) A high-strength bolted connection structure with no fire protection according to (3), wherein said high-strength bolt contains, in % by weight, C: 0.30 ~ 0.45%, Si: less than 0.10%, Mn: more than 0.40% ~ less than 1.00%, P: less than 0.010%, S: 0.010% or less, Cr: 0.5% or more ~ less than 1.5%, Mo: more than 0.35% ~ less than 1.5%, V: more than 0.3% ~ 1.0% or less, with the balance being Fe and unavoidable impurities, and wherein said high-strength bolt is an ultra-high-strength bolt having excellent fire resistance and a delayed fracture resistance satisfying equations <3> and <4> below:

$$TS \leqq (1.1 \times T + 850) \quad \text{<3>}$$

$$TS \leqq (550 \times Ceq + 1000) \quad \text{<4>}$$

where TS : tensile strength of the high strength bolt at room temperature (N/mm^2)

T : tempering temperature (°C)

Ceq : carbon equivalent (%)

$$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14).$$

(8) A high-strength bolted connection structure with no fire protection according to (4), wherein said high-strength bolt contains, in % by weight, C: 0.30 ~ 0.45%, Si: less than 0.10%, Mn: more than 0.40% ~ less than 1.00%, P: less than 0.010%, S: 0.010% or less, Cr: 0.5% or more ~ less than 1.5%, Mo: more than 0.35% ~ less than 1.5%, V: more than 0.3% ~ 1.0% or less, with the balance being Fe and unavoidable impurities, and wherein

said high-strength bolt is an ultra-high-strength bolt having excellent fire resistance and a delayed fracture resistance satisfying equations <3> and <4> below:

$TS \leqq (1.1 \times T + 850)$ <3>

$TS \leqq (550 \times Ceq + 1000)$ <4>

where TS : tensile strength of the high strength bolt at room temperature (N/mm^2)

T : tempering temperature (°C)

Ceq : carbon equivalent (%)

$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14)$.

(9) A high-strength bolted connection structure with no fire protection according to (5), wherein said high-strength bolt contains, in % by weight, C: 0.30 ~ 0.45%, Si: less than 0.10%, Mn: more than 0.40% ~ less than 1.00%, P: less than 0.010%, S: 0.010% or less, Cr: 0.5% or more ~ less than 1.5%, Mo: more than 0.35% ~ less than 1.5%, V: more than 0.3% ~ 1.0% or less, with the balance being Fe and unavoidable impurities, and wherein said high-strength bolt is an ultra-high-strength bolt having excellent fire resistance and a delayed fracture resistance satisfying equations <3>, <4> below:

$TS \leqq (1.1 \times T + 850)$ <3>

$TS \leqq (550 \times Ceq + 1000)$ <4>

where TS : tensile strength of the high strength bolt at room temperature (N/mm^2)

T : tempering temperature (°C)

Ceq : carbon equivalent (%)

$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14)$.

BRIEF DESCRIPTION OF DRAWINGS

Fig. 1 is a perspective view useful for explaining an example of a friction-type high-strength bolted connection structure of beam members to be connected

according to the present invention;

Fig. 2 is a sectional view useful for explaining an example of a friction-type high-strength bolted connection structure of brace members to be connected according to the present invention;

Fig. 3 is a partial perspective view useful for explaining an example of a friction-type high-strength bolted connection structure of beam to T-shaped joint metals to be connected and a tension-type high-strength bolted connection structure of column to T-shaped joint metals to be connected according to the present invention;

Fig. 4(a) is a partial sectional view useful for explaining an example of a friction-type high-strength bolted connection structure of beam to T-shaped joint metals and a tension-type high-strength bolted connection structure of column to T-shaped joint metals of Fig. 3;

Fig. 4(b) is a partial plan view useful for explaining Fig. 4(a);

Fig. 5 is a partial sectional view useful for explaining an example of a friction-type high-strength bolted connection structure of beam to T-shaped joint metals and a tension-type high-strength bolted connection structure of column to T-shaped joint metals in a case of a floor slab disposed on the upper part of the beam flange;

Fig. 6 is a view useful for explaining the relation between the tempering temperature and tensile strength (TS) of steel and the presence or the absence of a delayed fracture;

Fig. 7 is a view useful for explaining the relation between the carbon equivalent (Ceq %) and tensile strength (TS) of steel and the presence or the absence of a delayed fracture;

Fig. 8 is a view useful for explaining the relation between test temperature and shear proof stress ($TS/\sqrt{3}$) (in the case of M22 bolts);

Fig. 9 is a view useful for explaining the relation between test temperature and shear proof stress (TS/√3) (in the case of M16 bolts);

Fig. 10 is a view useful for explaining the relation between test temperature and shear proof stress (TS/√3) (in the case of M20 bolts);

Fig. 11 is a view useful for explaining the relation between test temperature and shear proof stress (TS/√3) (in the case of M24 bolts);

Fig. 12(a) is a partial sectional view useful for explaining an example of tension-type high-strength bolted connection structure of a column-beam provided with a floor slab (in the case of two bolts for T-shaped joint metal in the floor slab);

Fig. 12(b) is a side view useful for explaining the T-shaped joint metal of Fig. 12(a);

Fig. 12(c) is a plan view useful for explaining Fig. 12(a);

Fig. 13(a) is a partial sectional view useful for explaining an example of tension-type high-strength bolted connection structure of a column-beam provided with a floor slab (in the case of four bolts for T-shaped joint metal in the floor slab);

Fig. 13(b) is a side view useful for explaining the T-shaped joint metal of Fig. 13(a); and

Fig. 13(c) is a plan view useful for explaining Fig. 13(a).

THE MOST PREFERRED EMBODIMENT

Description of the embodiments of the invention

The present invention is directed to a high-strength bolted connection structure, that is, a friction-type high-strength bolted connection structure and a tension-type high-strength bolted connection structure. The invention uses ultra-high-strength bolts which can assure adequate strength (shear proof stress) at room temperature and at high temperature of 650°C, and which

do not give rise to the problem of delayed fracture. Thus, the invention allows the number of bolts to be decreased and the length of joint metal to be reduced so that the overall cost and the work execution time can be reduced, and a high-strength bolted connection structure with no fire protection can be realized that does not depend on a refractory covering or a protective structure using a refractory material.

A high-strength bolted connection structure, which includes a friction-type high-strength bolted connection structure and a tension-type high-strength bolted connection structure, is to be designed, in accordance with "Guide for design and work execution of high-strength bolted connection" published in 1973 and amended in 1993 by Architectural Institute of Japan, such that a friction-type connection and a tension-type connection are treated independently of each other in long-term design at room temperature and in anti-seismic design. Therefore, in the present invention, too, the high-strength bolted connection structure at high temperature will be described separately for the two types of connection structure, and the high-strength bolted connection structures with no fire protection, that is, a friction-type high-strength bolted connection structure with no fire protection and a tension-type high-strength bolted connection structure with no fire protection, are provided in accordance with the concept of verification of fire resistant security of respective types of connection.

In the present invention, both in the case of a friction-type high-strength bolted connection structure and in the case of a tension-type high-strength bolted connection structure, the high-strength bolted connection structure with no fire protection is realized basically by using ultra-high-strength bolts which have a bolt tensile strength at room temperature of not less than 1200 N/mm^2 and not more than 1600 N/mm^2 and which have

excellent shear proof stress at 650°C, that is, excellent fire resistance and excellent resistance to delayed fracture (including torshear-type high-strength bolts, hereinafter referred to as "ultra-high-strength bolts").

A steel material as disclosed, for example, in Japanese Patent Publication No. 2002-276637 filed by the present applicant is suitable to be used as the steel material for high-strength bolts having excellent fire resistance for realizing the present invention. As the steel material disclosed in that invention is characterized by excellent resistance to delayed fracture, and it has adequate strength at room temperature and also at a high temperature of 650°C, it is highly suitable to be used as the material for ultra-high-strength bolts having excellent fire resistance for realizing the high-strength bolted connection structure, with no fire protection, of the present invention.

For example, this steel material may be rolled to a wire rod and, from the wire rod, high strength bolts having the bolt thread of, for example, M22 may be formed, and with appropriate quenching and tempering, the tensile strength of the bolts may be adjusted to the range of 1200 ~ 1600 N/mm^2 to obtain the ultra-high-strength bolts, having excellent fire resistance and excellent resistance to delayed fracture, to be used in the present invention. As disclosed in the invention of above-mentioned Japanese Patent Publication No. 2002-276637, in order to relax the stress concentration in the bolt thread, it is effective to form this ultra-high-strength bolts in shape such that bottom shape of the bolt thread is in the form of arch-like curve.

The ultra-high-strength bolts having excellent fire resistance and excellent resistance to delayed fracture used in the present invention may be applied to all sites. However, as the required characteristics may differ depending upon the application site, it is possible to strictly select application sites depending

upon the required characteristics and to thereby reduce the burden of material cost.

In the high-strength bolted connection structure of the present invention, high-temperature strength, especially the level of the shear proof stress, of the high-strength bolts is required to be high. However, as the same shear stress as in the high-strength bolts does not act upon nuts and washers at the time of a fire when the bolted connection changes into pressure bearing state, the same high-temperature strength is not required for them and, therefore, general structural high-strength hexagon nuts and structural high-strength plain washer having no defined fire resistance may assure adequate high temperature strength.

Columns and beam members, or joint metal, used in the high-strength bolted connection structure to which the present invention is applied, may be all formed of fire resistant steel material having adequate high-temperature strength at 600°C or higher, for example, NSFR400B, 490B, etc. However, as the required characteristics may differ depending upon the application site, it is possible to strictly select application sites for fire resistant steel material having adequate high-temperature strength at 600°C or higher, which imposes large cost burden, and to thereby reduce the burden of material cost.

Next, the present invention will be described in detail.

1. Case of friction-type high-strength bolted connection structure

(1) Example of friction-type high-strength bolted connection structure

A friction-type high-strength bolted connection is a connection method in which joint members are tightly clamped via high strength bolts so as to transmit stress by the frictional force produced between members. Representative friction-type high-strength bolted

connection structures include, for example, a high-strength bolted connection structure as shown in Fig. 1, in which H-shaped beam members 1a and 1b are joined by high-strength bolts 3 via outer splice plates 2a and inner splice plates 2b and side splice plates 2c, or a high-strength bolted connection structure as shown in Fig. 2, in which brace members 1d and 1e are joined by high-strength bolts 3 via upper splice plate 2d and lower splice plate 2e, or a high-strength bolted connection structure as shown in Fig. 3, in which a beam member 6 is connected to T-shaped joint metal 7 by high-strength bolts 9. The connection structure shown in Fig. 3 in which a beam member 6 is connected to T-shaped joint metal 7 by high-strength bolts 9 and the T-shaped joint metal 7 is connected to a column member 5 by high-strength bolts 8, includes a friction-type high-strength bolted connection structure and a tension-type high-strength bolted connection structure, and the connection structure connecting the T-shaped joint metal 7 to the column member 5 by the high-strength bolts 8 corresponds to a tension-type high-strength bolted connection structure to be described later.

The present invention is applied, in a first aspect, to the friction-type high-strength bolted connection structure.

(2) Concept of verification of fire resistant security of a friction-type high-strength bolted connection.

At the time of a high temperature due to fire, in the friction-type high-strength bolted connection structure in a steel structure, an introduced axial force is relieved and a sliding load is lowered due to relaxation of the bolts 3 and beam members (brace members) and splice plates and a decrease in Young's modulus of elasticity. However, since it is only required that the high-strength bolted connection can finally support the long term load, security of the high-

strength bolted connection in fire resistance design needs only to be evaluated in terms of bearing proof stress (long term allowable shear proof stress), and not in terms of sliding proof stress.

In accordance with equations (2. 3), (2. 4), Table 2. 2, Table 2. 3 defined in "Guide for design and work execution of high-strength bolted connection" published in 1973 and amended in 1993 by Architectural Institute of Japan (corresponding to F10T (JIS B 1186)), security of the high-strength bolted connection at the time of fire can be verified if shear proof stress of the bolt $b\tau t$ (N/mm^2) at high temperature satisfies the relation <1>:

$$b\tau t \geqq \mu \times N_0/(\nu \times bAs) \quad \langle 1\rangle$$

where $b\tau t$: shear proof stress of the bolt at high temperature (N/mm^2)

$b\tau t = TSt/\sqrt{3}$

TSt : tensile strength of the bolt at high temperature (N/mm^2)

μ : coefficient of slip at room temperature

N_0 : design bolt tension (N)

ν : safety factor for long term load

bAs : cross-sectional area of bolt shank (mm^2),

wherein the design bolt tension (N_0) is expressed, for example, in accordance with the aforementioned "Guide for design and work execution of high-strength bolted connection" published by Architectural Institute of Japan, as follows:

$$N_0 = 0.675 \times TS \times bAe$$

where TS : tensile strength of the bolt at room temperature (N/mm^2)

bAe : effective cross-sectional area of bolt thread (mm^2).

For example, when the coefficient of slip (μ) is 0.45 and safety factor for long term load (ν) is 1.5, the

equation <1> can be rewritten as equation <1a>:

$b\tau t \geq 0.2025 \times TS \times (bAe/bAs)$ <1a>.

In addition, it can be seen that if, for example, the tensile strength of the bolt at room temperature (TS) is 1400 N/mm^2 and (the effective cross-sectional area of bolt thread portion of the bolt/ cross-sectional area of bolt shank) (bAe/bAs) is 0.816 for M16, M20, M24 (JIS B 0123), and 0.832 for M22 (JIS B 0123), the condition that $b\tau t$ is, from equation <1a>, not less than 231 N/mm^2 for M16, M20, M24, and not less than 236 N/mm^2 for M22, needs only to be satisfied.

Further, the present inventors have found that, in the fire resistant design of a friction-type high-strength bolted connection structure, since the evaluation is based on long term allowable shear proof stress, the high-temperature proof stress of nuts and washers can be finally neglected although it may somewhat affect the sliding load. Therefore, special fire resistance is not required to be given to the structural high-strength nuts or structural high-strength plain washers used in the high-strength bolted connection of the friction-type connection structure.

Further, although columns, beams, and joint metal having assured high-temperature strength are basically used, if a fire protection is used on a part of columns and beams, columns and beams may be formed of material of a low high temperature strength to obtain a connection structure that has substantially no problem.

2. Case of tension-type high-strength bolted connection structures

(1) Examples of tension-type high-strength bolted connection structures

Tension-type high-strength bolted connection is a connection method in which stress in axial direction of high-strength bolts is transmitted, as in friction-type connection, using a compression force produced between

members by tightly clamping the high-strength bolts. Representative examples of tension-type high-strength bolted connection structure include, for example, a connection structure as shown in Fig. 3, Fig. 4(a), and Fig. 4(b), in which a column 5 and beams 6 (including composite beams) are connected, via T-shaped joint metal 7, by high-strength bolts 8 (the high-strength bolts connecting the T-shaped joint metal to a column will be referred to hereinafter as tension bolts 8). As shown in Fig. 3, Fig. 4(a), and Fig. 4(b), the T-shaped joint metal and the beam 6 are connected by high-strength bolts 9 in a friction-type high-strength bolted connection.

(2) Concept of verification of fire resistant security of a tension-type high-strength bolted connection.

In a tension-type high-strength bolted connection, when heated at the time of fire, thermal expansion of the beam is constrained by the column so that compression force from the beam is produced in the tension-type connection. However, as a sliding load is lowered, a long term load (long term allowable shear force of the beam) needs to be supported by bearing (shear) of the bolts. Usually, as shown in Fig. 5, for example, there is a floor slab 10 on the upper flange 6a of the beam 6, and therefore, one may suppose that the high-strength bolts 8a in the floor slab 10 have the shear proof stress at room temperature and the remaining high-strength bolts 8 have the shear proof stress of the bolts at high temperature. The T-shaped joint metal 7 and the beam 6 are connected by high-strength bolts 9a in the floor slab 10 on the upper flange 6a and by the high-strength bolts 9 on lower flange 6b in a friction-type high-strength bolted connection. Typically, there are provided studs 11 in the floor slab 10 with the function of fixing the floor slab 10 to the upper flange 6a of the beam 6 against shearing displacement.

On the other hand, in a cooling process, after

heating, at the time of fire, shrinkage of the beam 6 is constrained by the column 5 so that tension from the beam 6 is produced in the tension-type connection, and therefore, a long term load (long term allowable shear force of the beam) needs to be supported by bearing (shear) of bolts. In addition, a tension force due to shrinkage of the beam 6 acts as an additional axial force so that the high-strength bolt 8 in the lower flange 6b (and web) of the beam 6 where cooperation of the floor slab cannot be expected, may be broken. In this situation, one may suppose that the high-strength bolts 8a in the floor slab 10 on the upper flange 6a of the beam 6 have the shear proof stress at room temperature and remaining high-strength bolts 8 outside of the floor slab 10 on the upper flange 6a of the beam 6 have the shear proof stress of the high-strength bolts at a high temperature.

From what has been explained above, it can be concluded that the fire resistant security of tension-type high-strength bolted connection is determined by the cooling process after heating at the time of fire wherein the number of bolts that can support the long term load (long term allowable shear force of the beam) is less. Therefore, the fire resistant security of a tension-type connection can be verified by selecting the beam having the long term allowable shear force Qs (N) at room temperature as an upper bound such that not only relation <1> is satisfied, but also following relation <2> between the long term allowable shear force Qs (N) at room temperature and the shear proof stress at room temperature $b\tau$ (N/mm^2) and the shear proof stress at high temperature $b\tau t$ (N/mm^2):

$$Qs \leqq \{ns \times b\tau + (nf - ns) \times b\tau t\} \times bAs \quad \langle 2\rangle$$

where Qs : long term allowable shear force of the beam at room temperature (N)

$$Qs = fs \times Ab$$

fs : long term allowable shear proof stress of the beam (N/mm^2)

Ab : cross-sectional area of the beam (mm^2)

ns : number of tension bolts in the floor slab on the upper flange side of the beam

$b\tau$: shear proof stress of bolt at room temperature (N/mm^2)

$b\tau = TS/\sqrt{3}$

TS : tensile strength of bolt at room temperature (N/mm^2)

nf : number of tension bolts on the upper flange side of the beam

$b\tau t$: shear proof stress of bolt at high temperature (N/mm^2)

$b\tau t = TSt/\sqrt{3}$

TSt : tensile strength of bolt at high temperature (N/mm^2)

bAs : cross-sectional area of the bolt shank (mm^2)

For example, when a tension-type high-strength bolted connection as shown in Fig. 5 is composed of M22 bolts in the case of high temperature of 650°C, and shear proof stress of the bolt at room temperature ($b\tau$) is 815 N/mm^2 and shear proof stress of the bolt at high temperature of 650°C ($b\tau t$) is 238 N/mm^2 , the number of tension bolts 8 on upper flange 6a of the beam 6 (nf) is 4, for example, and the number of tension bolts 8a in the floor slab 10 on upper flange 6a of the beam 6 (ns) is 2, for example, and the cross-sectional area of the bolt axis (bAs) is 380 mm^2, then it can be seen that the long term allowable shear force of the beam at room temperature (Qs) can be selected, from equation <2>, to be 800 kN or lower.

The present inventors have found that, as a fire resistant design of the tension-type high-strength bolted connection is evaluated by shear proof stress of the bolt

at room temperature and at a high temperature, the high-temperature proof stress of nuts and washers can be neglected. Thus, the structural high-strength hexagon nuts and the structural high-strength plain washers used as nuts and washers in the tension-type connection are not required to be given any special fire resistance.

Although columns 5, beams 6, and joint metal 7 having assured high-temperature strength are basically used, if fire protection is used on a part of columns and beams, columns and beams formed of material of lower high-temperature strength can be used to obtain a connection structure that has substantially no problem.

3. Characteristics required for steel for high-strength bolt

As regards the steel for high-strength bolts used in the high-strength bolted connection structure with no fire protection, that is, friction-type high-strength bolted connection structure with no fire protection and tension-type high-strength bolted connection structure with no fire protection of the present invention, Japanese Patent Publication No. 01-191762 and Japanese Patent Publication No. 03-173745 disclose a steel material in which, in view of the fracture surface of bolts due to delayed fracture indicating grain boundary fracture, impurities such as Mo, Cr, and the like in the chemical components constituting a steel are reduced to strengthen the grain boundary, while, in view of texture control, Mo and Cr are added for high temperature tempering at 400°C or higher to give a property such that, even if hydrogen that is responsible for delayed fracture may enter into steel, the hydrogen does not readily lead to a fracture. As is disclosed in Japanese Patent Publication No. 05-9653, reduction of the impurity P results in reduction of P segregated in the grain boundary and is particularly effective for strengthening a grain boundary.

However, in the case of above-mentioned steel, if

hydrogen enters into steel components in excess of a certain concentration, a delayed fracture is still induced. Therefore, in order to further improve the resistance of bolts to delayed fracture, it is effective to obstruct entrance of hydrogen into steel components, or to reduce accumulation of hydrogen at prior austenite grain boundaries.

As is disclosed in, for example, Japanese Patent Publication No. 05-70890, a technology for suppressing entrance and diffusion of hydrogen into steel material by simultaneous addition of Si and Ni to steel components is proposed. However, such addition of Si not only impairs a cold forging property of the bolts, but also leads to an increased cost.

A steel for bolts is disclosed, in response to the needs as described above, by the invention in Japanese Patent Publication No. 07- 278735 which, by composite addition of elements Mo, Cr, V that give rise to notable secondary hardening at the time of tempering, exhibits tensile strength of 1200 N/mm^2 even when tempered at high temperature of not lower than 450°C, and has excellent resistance to delayed fracture. However, even in this case, there is a problem that, even if tempered at high temperature of not lower than 450°C, when tensile strength is adjusted to 1400 N/mm^2 or higher, delayed fracture occurs at higher rate.

The present inventors have found, as a result of intensive study conducted to resolve above-described problem, that an equation of the relation between the bolt tensile strength and tempering temperature, and an equation of the relation between the bolt tensile strength and carbon equivalent calculated from chemical components of a steel material can be deduced, and have confirmed that, by selecting the chemical components of a steel so as to satisfy the two equations, and by suitable quenching and tempering treatment, a steel material is obtained which can be heat-treated to give a bolt tensile

strength of 1200 N/mm^2 or higher and has excellent resistance to delayed fracture, and which is thus highly suitable to be used as a steel material for high-strength bolts.

On the other hand, it has been confirmed that the fire resistant temperature of the steel having Fe as the main component and containing C, Si, Mn can be improved by adding alloy elements Cr, Mo, V, for example, used in fire resistant steel, to obtain a fire resistant temperature level of 600°C or higher.

From the foregoing, the present inventors have found that the high-strength bolt having excellent resistance to delayed fracture and the high-strength bolt having excellent fire resistance have a common problem from the viewpoint of chemical components of steel material so that, by solving this common problem, an ultra-high-strength bolt can be obtained which has combined both characteristics and which can realize connection structure with no fire protection and which has excellent fire resistance at 650°C.

(1) Chemical components of steel for ultra-high-strength bolt

Examples of chemical components (% by weight) of steel highly suitable as the steel for ultra-high-strength bolts used in the high-strength bolted connection structure with no fire protection, that is, friction-type connection structure with no fire protection and tension-type connection structure with no fire protection, of the present invention, will be described below.

C is an element necessary to assure adequate tensile strength of steel by a quenching and tempering treatment. If the content of C is less than 0.30%, adequate strength at room temperature cannot be assured, and if C is added in excess of 0.45%, the toughness of steel is degraded. Therefore, the content of C is restricted to the range of not less than 0.30% ~ not more than 0.45%.

Si is an element necessary to deoxidize steel and effective for enhancing strength of steel. If the content of Si is 0.10% or more, the toughness of steel is degraded and the steel becomes notably more brittle. Also, as Si is an element which exhibits high solid solution hardening of ferrite, cold forging is difficult even when spherodization annealing is performed. In addition, since Si is an element which is likely to induce grain boundary oxidation at the time of heat treatment, and resistance to delayed fracture of bolts tends to be degraded due to its notch effect, the content of Si should be decreased as far as possible. Therefore, the content of Si is to be restricted to less than 0.10%.

Mn is an element that is effective for improving hardenability. However, if the content is 0.40% or lower, desired effect cannot be obtained, and if Mn is added in an amount of 1.00% or more, temper embrittlement is produced, leading to a degradation of resistance to delayed fracture. Therefore, the content of Mn is to be restricted to the range of more than 0.40% ~ less than 1.00%.

P is an element that segregates at the grain boundaries and lowers the grain boundary strength and degrades resistance to delayed fracture. P is also an element that, in hydrochloric acid which is a remarkably corrosive environment, increases the amount of corrosion of steel through its promoting effect on the hydrogen production at the steel surface, and therefore, a content of P is to be lowered as far as possible. If the content of P is 0.010% or more, amount of hydrogen entering into steel increases notably. Thus, the content of P is to be restricted to less than 0.010%.

S is an element that segregates at the grain boundaries and thereby promotes embrittlement of steel. Therefore, a content of S is to be lowered as far as possible. If content of S exceeds 0.010%, embrittlement of steel becomes notable. Thus, the content of S is to

be restricted to 0.010% or less.

Cr is an element that improves hardenability and high temperature strength of steel and is effective in giving steel the resistance to temper softening. If the amount of addition is less than 0.5%, the above-described effect cannot be obtained. Thus, in view of economy, the added amount is to be restricted to the range of 0.5% or higher ~ less than 1.5%.

Mo is an element that is most effective in improving high temperature strength and is also effective in improving the resistance to delayed fracture by permitting high temperature tempering. If the added amount is less than 0.35%, the effect described above cannot be obtained, and if the added amount is in excess of 1.5%, a solid solution of undissolved carbide in the mother phase is unlikely to be produced at the time of tempering, leading to degradation of ductility. Thus, the added amount is restricted to the range of more than 0.35% ~ less than 1.5%.

V is an element that improves strength (including high temperature strength) of steel by precipitating as minute nitrides and carbides at the time of tempering, and permits high temperature tempering, and is also effective in the size reduction of prior austenite particles. Further, the carbides and nitrides that precipitate at the time of tempering provide trap sites for hydrogen and are effective in remarkably improving the resistance to delayed fracture by decreasing the amount of hydrogen accumulated at grain boundaries. However, if the added amount is 0.3% or less, particle size No. 10 cannot be achieved for prior austenite particles, and therefore, the resistance to delayed fracture cannot be improved. If the added amount exceeds 1.0%, the cold forging characteristics of bolts are impaired. As V is an expensive element, economy must also taken into account so that the content is to be

restricted to the range of more than 0.3% ~ 1.0% or less.

(2) Tempering temperature characteristics

Since delayed fracture occurs as fracture at grain boundaries of prior austenite grains, in order to improve the resistance to delayed fracture, it is effective to avoid low temperature temper embrittlement region of 250 ~ 400°C. Further, in order to suppress segregation of film-formed cementite in prior austenite grain boundaries, it is effective to control the form of carbides by adopting higher tempering temperature. It is also effective to precipitate carbides and nitrides of V which serve as trap sites for hydrogen in order to decrease hydrogen accumulated in grain boundaries. Thus, it is possible to select a tempering temperature of 450°C or higher.

However, the present inventors were not restricted by the above-mentioned method, and have found, from experimental results, that the resistance to delayed fracture can be improved and delayed fracture can be reliably avoided by selecting tempering temperature satisfying the equation <3> of the relation between tensile strength TS (N/mm^2) of high-strength bolts and tempering temperature (°C) and the equation <4> of the relation between tensile strength TS (N/mm^2) of high-strength bolts and carbon equivalent Ceq (%).

By using a steel material satisfying these conditions to form high-strength bolts, ultra-high-strength bolts with tensile strength (TS) of bolts at room temperature of, for example, 1200 N/mm^2, and having excellent fire resistance with the shear proof stress ($b\tau t$) of bolts at 650°C satisfying the above-described relation <1> can be obtained, and by using these ultra-high-strength bolts, the friction-type high-strength bolted connection with no fire protection and the tension-type high-strength bolted connection with no fire protection can be realized.

$$TS \leqq (1.1 \times T + 850) \quad \langle 3\rangle$$

$$TS \leqq (550 \times Ceq + 1000) \quad \langle 4\rangle$$

where TS : tensile strength of high strength bolts at room temperature (N/mm^2)

T : tempering temperature (°C)

Ceq : carbon equivalent (%)

$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14)$.

[Examples of experimental tempering]

Using the inventive steel samples (1 ~ 10) having chemical compositions as shown in Table 1, wire rods of φ21.5 mm in diameter were subjected to hot rolling, and high-strength bolts with bolt thread of M22 were formed and adjusted by quenching and tempering to tensile strength of bolts in the range of 1200 ~ 1700 (N/mm^2) to obtain ultra-high-strength bolts.

The tensile strength of bolts was adjusted by the composition of the steel and the tempering temperature, with the tempering temperature in the range of 290 ~ 700°C. This tempering was performed to give high temperature conditions for evaluating high temperature characteristics. This tempering temperature T (°C) and tensile strength TS (N/mm^2) of ultra-high-strength bolts of experimental examples after tempering (steel samples 1 ~ 10) are shown in Table 2 together with the case of high-strength bolts of comparative examples (steel samples 11 ~ 18).

Figs. 6 and 7 show occurrence or non-occurrence of delayed fracture after tempering from large specific experimental data obtained using the inventive steel samples (1 ~ 10) and comparative steel samples (11 ~ 18) shown in Table 1 with × mark (occurrence of delayed fracture) and ○ mark (no occurrence of delayed fracture) in the Figures. Both Figures show that delayed fracture

did not occur in the region where above-mentioned relations <3> and <4> are satisfied.

Table 1

Steel sample	Chemical composition (wt%)												Ceq
	C	Si	Mn	P	S	Cr	Mo	Al	V	Ni	Ti	Nb	
1	0.40	0.07	0.42	0.005	0.009	0.61	1.20	0.020	0.56				0.935
2	0.34	0.04	0.79	0.007	0.003	1.21	0.99	0.015	0.36				0.989
3	0.34	0.03	0.66	0.002	0.002	0.98	0.50	0.062	0.67				0.820
4	0.39	0.07	0.50	0.008	0.008	1.21	0.58	0.025	0.35				0.888
5	0.39	0.05	0.51	0.005	0.009	1.21	0.57	0.021	0.34				0.886
6	0.40	0.08	0.81	0.005	0.008	0.58	0.22	0.019	0.35	0.65	0.04		0.751
7	0.40	0.05	0.54	0.08	0.008	1.00	1.00	0.032	0.32				0.942
8	0.44	0.03	0.85	0.005	0.004	0.90	1.45	0.020	0.70	0.50	0.02		1.188
9	0.43	0.05	0.80	0.005	0.003	1.01	1.20	0.033	0.40	0.20			1.100
10	0.42	0.05	0.75	0.003	0.004	0.83	1.10	0.030	0.40	0.10		0.020	1.020
11	0.41	0.08	0.95	0.007	0.001	1.41	0.93	0.072	0.40	0.00			1.115
12	0.31	0.06	0.50	0.018	0.007	1.01	0.60	0.032	0.29	0.00			0.769
13	0.34	0.17	0.76	0.015	0.017	1.00	0.17	0.025	0.00	0.00			0.716
14	0.19	0.08	0.97	0.013	0.004	0.15	0.00	0.032	0.00	0.00			0.385
15	0.40	0.23	0.81	0.005	0.008	0.58	0.22	0.019	0.00	0.65	0.04		0.732
16	0.32	0.21	0.62	0.010	0.008	1.25	0.59	0.027	0.00	0.00	0.02	0.002	0.830
17	0.30	0.94	0.49	0.011	0.006	1.99	0.20	0.074	0.00	0.00			0.869
18	0.32	0.99	0.46	0.007	0.006	1.97	0.40	0.027	0.00	0.00			0.932

$$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14)$$

Table 2

	Steel sample	Tempering temperature (°C)	Tensile strength TS (N/mm^2)	TS ≤ 1.1 T + 850	TS ≤ 550 Ceq + 1000	Limiting diffusive hydrogen (ppm)
Experimental examples	1	550	1338	○	○	1.54
	2	550	1408	○	○	0.91
	3	500	1362	○	○	1.54
	4	625	1426	○	○	1.40
	5	650	1312	○	○	1.70
	6	450	1316	○	○	0.70
	7	570	1470	○	○	0.90
	8	700	1605	○	○	0.95
	9	660	1550	○	○	1.05
	10	640	1502	○	○	1.20
Comparative examples	11	525	1652	×	×	0.12
	12	440	1469	×	×	0.29
	13	390	1567	×	×	0.05
	14	290	1384	×	×	0.09
	15	435	1482	×	×	0.40
	16	450	1473	×	×	0.45
	17	450	1497	×	×	0.25
	18	400	1651	×	×	0.10

$Ceq = C + (Mn/6) + (Si/24) + (Ni/40) + (Cr/5) + (Mo/4) + (V/14)$

Relation satisfied : ○ Relation not satisfied : ×

Example

Example 1

Example 1 is a case of friction-type high-strength bolted connection structure in which, as shown in Fig. 1, beams 1a, 1b are connected via outer splice plate 2a, inner splice plate 2b and side splice plate 2c by high-strength bolts 3 and in which the beams 1a, 1b, outer splice plate 2a, inner splice plate 2b and side splice plate 2c are formed of material having assured high-temperature strength at 650°C.

Fig. 8 is a view showing, for high-strength bolts with bolt thread of M22 (JIS B 0123), the relation between shear proof stress $TS/\sqrt{3}$ (N/mm^2) of a ultra-high-strength bolts of the present invention and a test temperature (°C) together with the cases of Comparative example 1 (general F10T (JIS B 1186) bolt), and Comparative example 2 (fire resistant F10T (JIS B 1186) bolt). The ultra-high-strength bolts of the present

invention have the tensile strength at room temperature adjusted by heat treatment to 1400 N/mm^2 or higher, and long term allowable shear proof stress of this ultra-high-strength bolts is 236 N/mm^2. The long term allowable shear proof stress of Comparative example 1, 2 is 147 N/mm^2.

Fig. 8 shows that the ultra-high-strength bolts of the present invention have tensile strength at room temperature of 1412 N/mm^2 (= 815 N/mm^2 $\times$ $\sqrt{3}$), and have the shear proof stress at 650°C ($b\tau t$) of the bolt satisfying above-described relation <1> and the shear proof stress at 650°C ($b\tau t$) is 1.3 times that of Comparative example 2.

Figs. 9, 10, and 11 show, for ultra-high-strength bolts of the present invention having bolt thread of M16, M20, and M24, respectively, the relation between the shear proof stress TS/$\sqrt{3}$ (N/mm^2) and test temperature (°C). Each of the Figures shows that the ultra-high-strength bolts of the present invention have the shear proof stress of the bolt at 650°C ($b\tau t$) satisfying the relation <1>.

Example 2

Example 2 is a case of tension-type high-strength bolted connection structure in which, as shown in Fig. 5, a column 5 and T-shaped joint metal 7 are connected by high-strength bolts 8 and there is a floor slab 10. The column 5 and the T-shaped joint metal are formed of material having assured high temperature strength at 650°C, and the beams are formed of material having tensile strength in the 400 N/mm^2 class.

Figs. 12 and 13 show examples of a tension-type connection in which a column 5 and a T-shaped joint metal 7 are connected by high-strength bolts having bolt thread of M22 (JIS B 0123) and number of tension bolts 8a in the floor slab 10 on upper flange 6a of the beam 6 are,

respectively, two and four.

Table 3 shows examples of the upper bound of selectable beam cross section (H-section beam), for the high-strength bolted connection structure of Figs. 12 and 13, that is determined from long term allowable shear proof stress Qs of the beam at 650°C using the above-described relation <2> based on numerical values indicated in Fig. 8. From Table 3, it can be seen that the ultra-high-strength bolts of the present invention permit a beam having the section H-400×200×8×13 to be selected in the case where number of tension bolts 8a in the floor slab 10 is two (Fig. 12), and a beam having the section H-600×200×12×22 to be selected in the case where number of tension bolts 8a in the floor slab 10 is four (Fig. 13), and that a beam having larger long term allowable shear proof stress Qs can be selected than with bolts of the Comparative examples.

Table 3

		High strength bolt	Tension type connection	Number of bolts on upper flange side of beam: nf	Number of bolts in floor slab on upper flange side of beam: ns	Long term allowable shear force of beam: Qs	Example of upper bound of selectable beam section (for tensile strength of 400 N/mm^2 class)
Comparative example	1	General F10T bolt	Fig. 12	4	2	557kN or less	H-350×175×7×11
			Fig. 13	6	4	1,023kN or less	H-600×200×9×12
	2	Fire resistant F10T bolt	Fig. 12	4	2	620kN or less	H-350×175×7×11
			Fig. 13	6	4	1,096kN or less	H-600×200×9×16
Inventive example		Fire resistant ultra-high strength bolt	Fig. 12	4	2	800kN or less	H-400×200×8×13
			Fig. 13	6	4	1,420kN or less	H-600×200×12×22

From what has been described in the foregoing, it can be confirmed that the ultra-high-strength bolts of the present invention have excellent fire resistance (high temperature strength) and excellent resistance to delayed fracture at room temperature and at high temperature of 650°C, and these characteristics fully satisfy the provisions of "Guide for design of high strength bolts" published in 1973 and amended in 1993 by Architectural Institute of Japan, and that, by using these ultra-high-strength bolts, high-strength bolted connection structures with no fire protection, that is, friction-type high-strength bolted connection structures with no fire protection and tension-type high-strength bolted connection structures with no fire protection, can be realized.

The present invention is by no means restricted to structures and examples as described above, and conditions of the connection structure and conditions of high-strength bolts (including fire resistant steel used for construction) may be modified depending upon the connection to be formed, site of usage, and environmental conditions, within the scope of the appended claims.

The present invention presupposes that, in high-strength bolted connection structure forming steel structure for which fire resistance is required, main members to be connected (for example, columns, beams, or braces) have, basically, an adequate high-temperature strength at 650°C and can realize connection structures with no fire protection, and in order to fully exploit the high-temperature strength of these main members (for example, pillars, beams, or braces), the present invention uses ultra-high-strength bolts having, for example, a 1.4 times or more larger bolt tensile strength at room temperature than conventional F10T bolts and a 1.3 times larger shear proof stress at 650°C than conventional fire resistive F10T bolts to realize a high-strength bolted connection structure with no fire

protection at high temperature of 650°C, to thereby realize reduction of cost as well as reduction of work execution time.

For nuts and washers used in the present invention, when the bolted connection passes to a bearing state at the time of a fire, the same shear stress as in high strength bolt does not act on nuts and washers, so that general high-strength hexagon nuts and structural high-strength plain washers for which no fire resistance is required may be used to avoid a cost increase.

Further, a part of beam members and joint metal used in the present invention can be strictly selected depending upon the site of usage to thereby reduce the material cost and work execution time.